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Performance of a direct detection camera for off-axis electron holography

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ABSTRACT

The performance of a direct detection camera (DDC) is evaluated in the context of off-axis electron holographic experiments in a transmission electron microscope. Its performance is also compared directly with that of a conventional charge-coupled device (CCD) camera. The DDC evaluated here can be operated either by the detection of individual electron events (counting mode) or by the effective integration of many such events during a given exposure time (linear mode). It is demonstrated that the improved modulation transfer functions and detective quantum efficiencies of both modes of the DDC give rise to significant benefits over the conventional CCD cameras, specifically, a significant improvement in the visibility of the holographic fringes and a reduction of the statistical error in the phase of the reconstructed electron wave function. The DDC's linear mode, which can handle higher dose rates, allows optimisation of the dose rate to achieve the best phase resolution for a wide variety of experimental conditions. For suitable conditions, the counting mode can potentially utilise a significantly lower dose to achieve a phase resolution that is comparable to that achieved using the linear mode. The use of multiple holograms and correlation techniques to increase the total dose in counting mode is also demonstrated.

1. Introduction

The advent of commercially available direct detection cameras (DDC) for transmission electron microscopy (TEM) offers the capacity to reduce the noise level in images and diffraction patterns to essentially that of the Poisson noise of the electron beam. While conventional charge-coupled device (CCD) cameras used in TEM rely on fibre-optically coupled photons as intermediate signal carriers in order to separate and hence protect the complementary metal-oxide semiconductor (CMOS) technology from the beam electrons, DDCs operate via the production of electron–hole pairs generated directly by the beam electrons impinging on a back-thinned CMOS structure. For sufficiently low dose rates, their design can enable significant improvements in the detective quantum efficiency (DQE) and the modulation transfer function (MTF) compared to conventional CCD cameras [1–3]. Hence, the existing literature on DDCs is predominantly focused on structural biological applications, where obvious advantages are gained under the necessarily low dose conditions, e.g., typically $<10\ e^{-}\,\text{Å}^{-2}$. For example, DDCs have been utilised for resolving high-resolution structural information in biological materials in cryo-EM [4–6]. Consequently, the characteristics of DDCs at dose rates and spatial resolutions applicable to biological materials are already documented. In many other areas of TEM, the dose rate used is typically of the order of $1000\ e^{-}\,\text{Å}^{-2}$, and the spatial resolution can vary from better than 1 Å to a few nanometers. Hence, in these contexts, which includes off-axis electron holography, there have been no demonstrations of DDCs to the best of our knowledge.

Here, we evaluate the applicability and performance of a DDC for off-axis electron holography in TEM, which is an established technique for measuring the electrostatic and magnetic properties of materials and devices. The technique allows the phase shifts experienced by the electron beam wavefield to be reconstructed and uses them to map the spatially varying electric or magnetic field of the sample. In order to measure the increasingly weaker electric and magnetic fields generated from nanomaterials, it is necessary to improve the resolution of the reconstructed phase for a given spatial resolution. Here we evaluate the phase resolution afforded by employing a DDC and compare it with that obtained

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with a conventional CCD camera.

The phase resolution in an electron hologram is governed primarily by two competing factors: the transverse spatial coherence and the electron dose. In the past, improvements in phase resolution have been made with the use of brighter electron sources [7–10] and by increased microscope stability which enables longer exposure times and hence a greater total dose [11]. Greater total doses and hence better phase resolution have also been achieved by combining data from multiple holograms [12–17]. In previous work [18], we reported the optimum dose rate and exposure time to achieve the best phase resolution for a given instrument and spatial resolution. In that work, the instrument was fitted with a conventional CCD camera and it was justifiably assumed that the camera performance was independent of dose rate (within reasonable limits). Since DDCs can offer an improved MTF and DQE, with the caveats that these quantities can be dose-rate dependent and that their optimum performance requires low dose rates, it is the aim of this paper to evaluate the performance of a DDC and discuss its potential for off-axis electron holography.

2. Background

The DDC used in this study is the K2 Summit (Gatan, Inc.). It has 3838 × 3710 pixels, with a pixel size of 5 μm. The camera can be operated in three different modes: "counting", "super-resolution" and "linear". In the former two modes, the underlying frame rate is 400 Hz (regardless of the frame rate set by the user). In the counting mode at a low dose rate, individual incident electrons are identified and digitised as a discrete count at a particular pixel. Higher dose rates mean that there is a significant probability that more than one electron is incident within a cluster of neighbouring pixels per 1/400 s frame, and since the counting algorithm used by the K2 cannot distinguish between single or multiple electron events, this results in so-called "coincidence losses". Therefore, the counting mode MTF and DQE are highly dependent on the dose rate. For example, at 1 e^{-} $pixel^{-1}$ s^{-1} (eps) the DQE at zero spatial frequency is nearly equal to unity, but at 10 eps it decreases by over 14% [3]. The super-resolution mode shares many similarities with counting mode, except for the crucial point that the resolution dictated by the physical pixel size is overcome by using an algorithm that locates the position of incident electrons to sub-pixel accuracy, resulting in images composed of four times as many pixels (7676 × 7420). This results in a further increase of the MTF compared to counting mode, though the increase is perhaps not as large as would be expected, and occurs at the cost of four times the (already very large) amount of data. Therefore, in this paper we do not explicitly consider super-resolution mode. In contrast to the counting mode, the linear mode of the K2 operates by accumulating the charge carriers generated by the impinging beam electrons during a user-set exposure time, which is then read out to provide an image. The latter mode is somewhat akin to conventional CCD cameras, though the readout time of the K2 is much shorter and does not require beam blanking, which is also a very significant advantage for many applications including electron holography.

Due to its ability to count individual electron events, the counting (and super-resolution) mode of the K2 camera is essentially free of readout noise, except for extremely low dose rates, i.e., $\lesssim$0.1 eps. For dose rates between 1 and 15 eps, it has been demonstrated to have high MTFs [2]. At dose rates higher than 20 eps, the MTF drops significantly due to coincidence losses [1,3]. In contrast, the linear mode, while not offering the benefits of single electron counting, is capable of dose rates similar to those of a conventional CCD camera, and does not suffer from coincidence losses. In addition, the absence of fibre optics in the DDC means that the pixel-scale distortions usually present in conventional CCD camera images are absent. Hence in the context of off-axis electron holography, the a posteriori correction for such distortions is not required.

In the present work, the performance of the K2 counting and linear modes is directly compared with that of an UltraScan 1000 XP CCD camera (Gatan, Inc). The latter camera has 2048 × 2048 pixels with a 14 μm pixel size.

3. Methods

The experiments were carried out using a Titan 80-300 FEG-TEM (FEI Co.) operated at 300 kV. The microscope was equipped with an ultra-bright X-FEG electron gun, and two biprisms located in the first and second selected area aperture planes, separated by an "extra lens". Both cameras were mounted on the TEM with the K2 located downstream of the UltraScan. The microscope was operated in the standard mode with the objective lens turned on (as opposed to Lorentz mode where the objective is off). Blank holograms (no specimen) were recorded using the second biprism with the extra lens off (the first biprism was not used). The biprism voltage was set to 150 V, which produces a fringe spacing of 83 pm at the specimen plane. The magnification was 180 kX for the K2 (pixel size corresponding to 16.6 pm at the specimen plane) and 450 kX for the UltraScan (a pixel size of 17.3 pm at the specimen plane). The relative values of these magnifications were chosen to compensate for fact that the two cameras have different physical pixel sizes and are located in different optical planes. Hence, the sideband positions are at 0.20 $pixel^{-1}$ for the K2 and 0.21 $pixel^{-1}$ for the UltraScan, i.e., the number of pixels per holographic fringe is very similar. This enables us to attribute any differences in the camera performances solely to their MTF and DQE performances. The calibrated values of the magnifications enabled us to track and hence correct any drift of the hologram throughout the experiment.

Although the above experimental conditions are suitable for electron holography at high spatial resolution, as described later, our results are applicable to other conditions, e.g., Lorentz mode (objective lens off) conditions suitable for magnetic field measurements.

Details regarding the Fourier processing of holograms can be found in Reference [18].

For simplicity, all of our experiments used round illumination and the beam intensity was varied using the C2 lens excitation only. The electron doses mentioned throughout this paper were calculated from the central regions of the holograms where intensity fluctuations from Fresnel fringes are minimised. For the UltraScan, the conversion of ADC counts to electron counts was calibrated by measuring the beam current using a picoammeter connected to the drift tube of a Gatan Imaging Filter (Gatan Inc.). For the K2 counting mode, the dose rate was read directly from the manufacturer's software default value. For the K2 linear mode, the conversion of analog-to-digital converter (ADC) counts to electron counts was calibrated using a dose rate of 1 eps in counting mode as a reference. Since the software default dose rate that was used is based on an average over many cameras, it is expected to be within 10–15% of the real value of the camera tested. However this is still useful for providing an explanation for the comparison of the two modes of K2 with the CCD camera, as the K2 linear and counting modes were cross-calibrated, and dose rate of the CCD camera was independently calibrated. Hence the ratio of DQEs between the K2 and the CCD camera should still be accurate. Doses are quoted in units of electron counts per unit area at the specimen plane, unless otherwise specified.

Important attributes of the camera for electron holography are